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TOWARD A VIABLE STRATEGY FOR ESTIMATING VIBROTHERMOGRAPHIC PROBABILITY OF DETECTION (PREPRINT)

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14. ABSTRACT
Vibrothermography is a technique for finding cracks and delaminations through infrared imaging of vibration-induced heating. While vibrothermography has shown remarkable promise, it has been plagued by persistent questions about its reproducibility and reliability. Fundamentally, the crack heating is caused by the vibration, and therefore to understand the heating process we must first understand the vibration process. We lay out the problem and begin the first steps toward relating detectability to the local motion around a crack as well as the crack size. A particular mode, the third-order free-free flexural resonance, turns out to be particularly insensitive to the presence of clamping and transducer contact. When this mode is excited in a simple bar geometry the motions of the part follow theoretical calculations quite closely, and a single point laser vibrometer measurement is sufficient to evaluate the motion everywhere. Simple calculations estimate stress and strain anywhere in the bar, and these can then be related to observed crack heating.

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Keywords: Vibrothermography, Sonic IR, Sonic Infrared, Crack Detection
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INTRODUCTION

Vibrothermography, also known as sonic infrared or thermosonic nondestructive testing, shows substantial promise as an alternative to fluorescent penetrant inspection (FPI) for turbine components [1]. In vibrothermography, a specimen is excited with high amplitude vibration or ultrasound and observed with an infrared camera. The vibration causes cracks to heat through some sort of frictional process. Impressive demonstrations provide dazzling pictures of glowing cracks. Vibrothermography has even been shown to detect some cracks that are missed with FPI [2]. Nevertheless persistent questions about the reliability and the reproducibility of vibrothermographic inspection have limited its acceptance. In order to widely deploy vibrothermography, a more solid physical understanding of the crack heating process is needed to permit meaningful extrapolation of POD test data to actual parts.

REPRODUCIBILITY

To date, vibrothermographic inspections have not had the reproducibility desired for a robust inspection. Repeated testing of a single crack in nominally similar conditions can generate dramatically different amounts of heat, as shown in Fig.1. Sometimes a hit/miss analysis applied to the measured data hides the underlying variability. With a better understanding

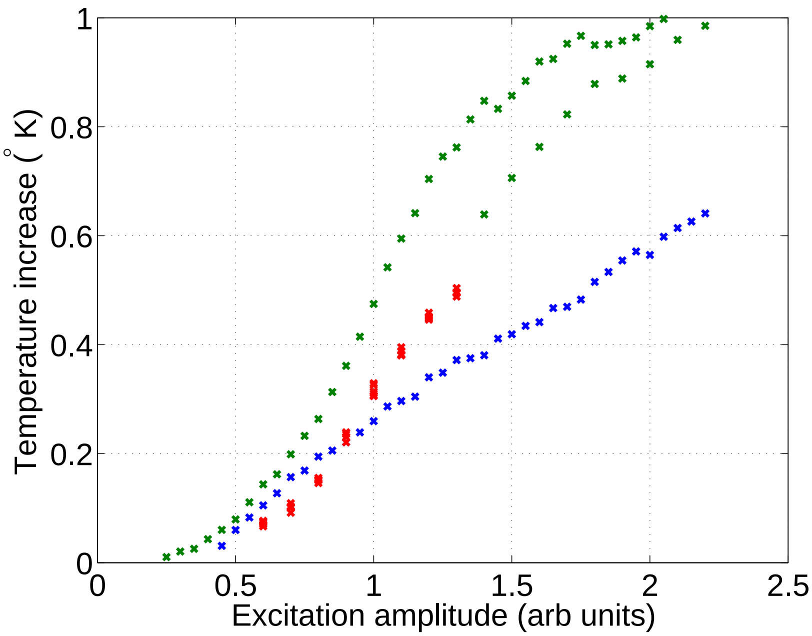


FIGURE 1. Nominally equivalent measurements can give dramatically different results.

of the physics, we can at least try to understand the sources of variation and minimize those that can be controlled. Fundamentally the heating of a crack in response to vibration is determined by *intrinsic* properties of the crack and its local vibration. These intrinsic properties include crack morphology, crack condition, crack size, and crack motion. Crack condition can be affected by contaminants and may also change over time due to vibration-induced rubbing of the crack faces or corrosion. Crack motion is a complicated function of the vibrational excitation, specimen geometry, and mounting conditions. The focus of this paper will be on measuring crack motion in simple geometries so as to factor out the effect of variations in excitation and clamping conditions and instead relate crack heating to the dynamic stress applied to the crack.

PROBABILITIES OF DETECTION

The accepted procedure for qualifying new inspections involves developing a probabilistic model of flaw detectability. Typically a probability-of-detection (POD) curve represents POD as a function of crack size. Other sources of detectability variation are either ignored (leading to scatter in the POD data), corrected for, or eliminated through careful design of measurement procedures. In the case of vibrothermography, the dependence of heating on vibration is too fundamental to ignore. Since vibration is different everywhere in the specimen, a proper POD study would have to independently evaluate probabilities of detection for cracks of every possible position and orientation. Obviously such a study would be cost-prohibitive unless it is possible to extrapolate all those probabilities of detection from a relatively small number of physical measurements of crack motion and heating. The key to extrapolation is to measure the dependence of crack heating on crack motion in test specimens of simple geometries. Probabilities of detection in real specimens can be estimated by predicting heating through the measured dependence of heating on motion for the actual vibrations excited in the inspection and all the possible crack positions and orientations. Thus a useful POD study of test specimens will relate crack heating to crack motion and crack size.

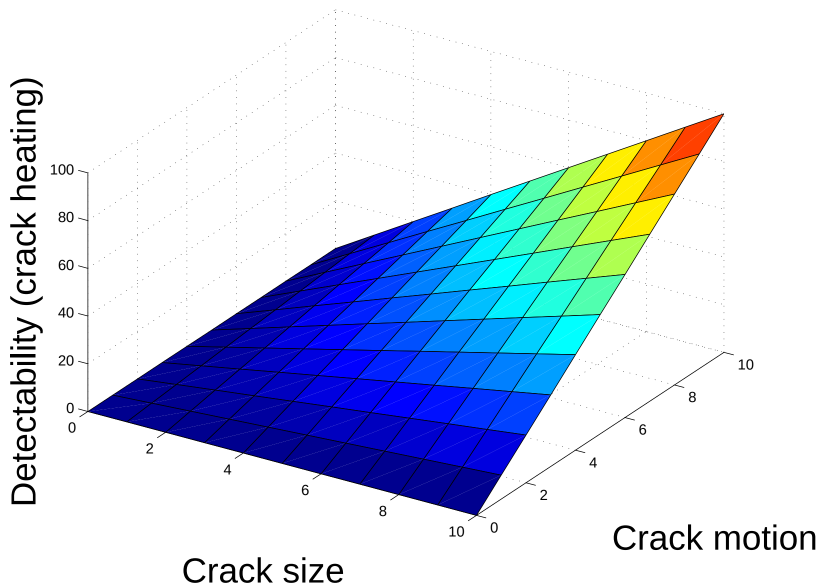


FIGURE 2. Detectability is a function of both crack size and crack motion.

An oversimplified hypothetical POD surface relating detectability to crack size and motion is shown in Fig.2. Obviously crack motion cannot (yet) be represented as a scalar and should consider the effect of frequency and all six independent components of the dynamic stress or strain tensor.

MEASURING CRACK MOTION

A prerequisite to such a POD study is an adequate method for measuring crack motion. Simulation is ineffective because adequate dynamic models for mechanical mounts and vibration source do not exist. For complicated geometries, boundary measurement of surface velocities, combined with a boundary integral of the Green's function can be used to evaluate internal motions, stresses, and strains, as discussed elsewhere [3, 4]. A simpler alternative is to use resonances. If the specimen is vibrating in a known resonant mode, then a single point laser vibrometer measurement, combined with the known mode shape (calculated from simulation or theory) is sufficient to evaluate the motion everywhere in the specimen. The resonant method for determining motion requires mounting and excitation that does not disrupt the structure of the resonance. This may be difficult for actual test parts, but is more reasonable for test specimens of simple geometries where mounting points can be selected to coincide with nodes of the resonance and therefore have a minimal effect on the mode-shape. The third-order flexural resonance of a bar turns out to be particularly insensitive to clamping conditions, especially when clamped with soft (rubber) pins. This resonant mode is used in the experiments described below to relate crack heating to normal open-close motion of a crack.

ETC EXPERIMENT

Iowa State University, Pratt & Whitney, and General Electric will be measuring vibration induced crack heating in a set of 75 titanium and 75 Inconel® samples as part of the Engineering Titanium Consortion (ETC) thermal acoustics program. The ultimate goal of these

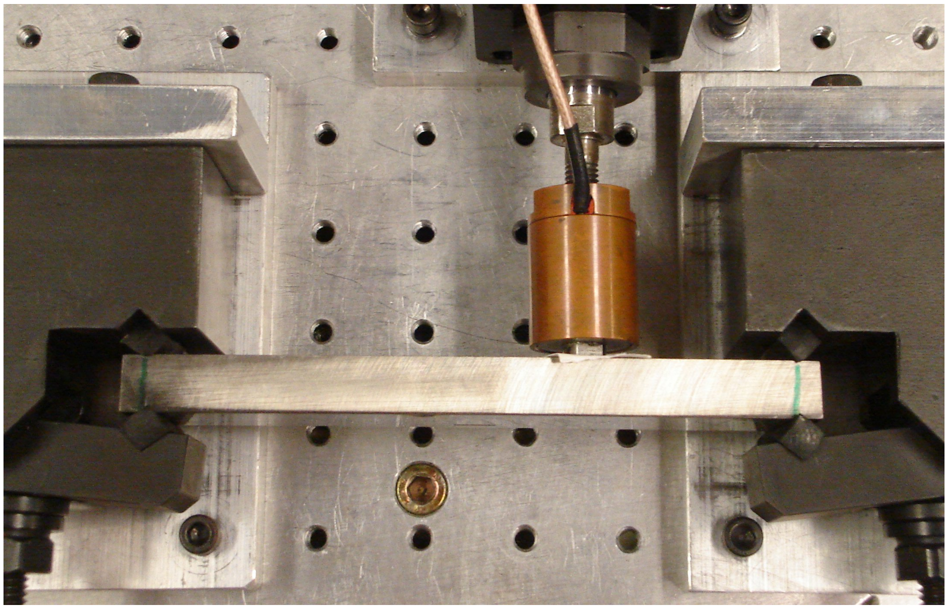


FIGURE 3. Clamp configuration for ETC sample

experiments will be to provide an extrapolatable data set for POD estimation. As such we will need to relate heating to the intrinsic properties of the crack and the local motion of the specimen near the crack. Using a known resonance, extraction of intrinsic information such as the state of stress at the crack is possible from a single point vibrometer measurement.

For the rectangular bar geometry used here the third order free-free flexural mode of vibration is observed to be particularly insensitive to the presence of rubber pins used to grip the sample as shown in Fig. 3. The third order mode is useful because the ETC specimen set can be modified to place the third-order resonance at the 20 kHz frequency of the ultrasonic welders used as a vibration source at Pratt & Whitney and General Electric by simply cutting the test specimen shorter.

The frequency response of an ETC sample prior to cutting is shown in Fig. 4. The peaks have been labeled with the corresponding vibration mode identified using finite element simulation and elementary flexural wave theory. Cutting the test specimens shorter in length increases the frequency of their third-order flexural resonance as illustrated in Fig. 5, which shows the third order flexural resonant frequency of three ETC specimens successfully tuned to 20 kHz. The entire ETC specimen set will be tuned in this fashion. The deformed shape of the 3rd order flexural mode, shown in Fig. 6, is measured by scanning over the face of the specimen with the vibrometer and exciting the specimen at each scan point. Fig. 6 also shows the expected mode shape from flexural wave theory and it matches the measured shape almost exactly.

For a specimen in resonance the normal stress is easily calculated from a single point vibrometer measurement. Using flexural wave theory the flexural stress at the center of the front face is

$$\sigma|_{x=0} = \frac{iEh}{2\pi f}\kappa^2 \left(\frac{\frac{\cos \kappa L/2}{\cosh \kappa L/2} - 1}{\frac{\cos \kappa L/2}{\cosh \kappa L/2} + 1} \right) \dot{u}|_{x=0} \,. \tag{1}$$

Equation 1 is applicable at the center of a rectangular specimen in odd-order free-free resonant flexural bending. E is Young's modulus, L & h are the length and height, and κ is the flexural wave number at frequency f. Using Equation 1 the measured motion, $\dot{u}$, can be

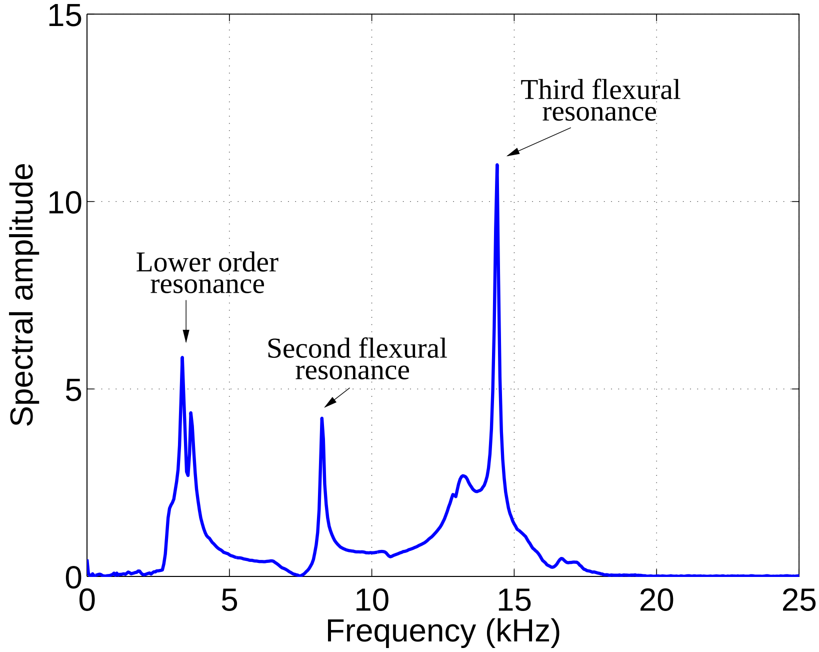


FIGURE 4. Measured spectrum of uncut ETC sample

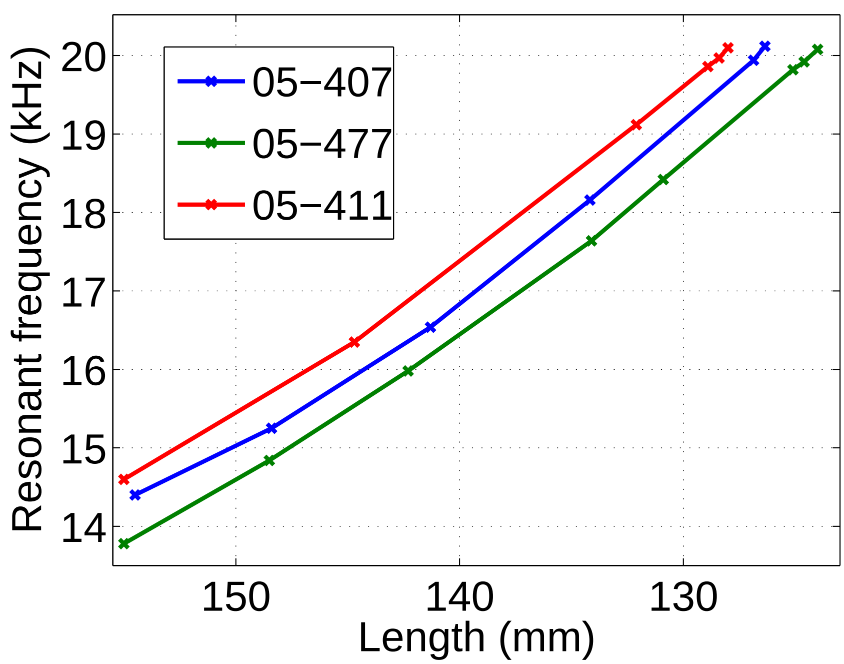
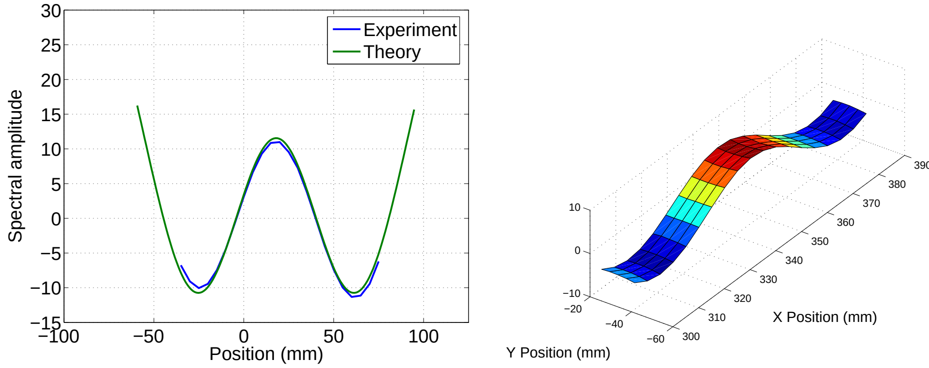


FIGURE 5. Each line corresponds to the tuning process for a particular specimen. As the samples are cut shorter the resonant frequency increases.



(a) (b)

FIGURE 6. (a) X-axis motion profile: measured and calculated from flexural wave theory (b) 3D plot of measured motion profile

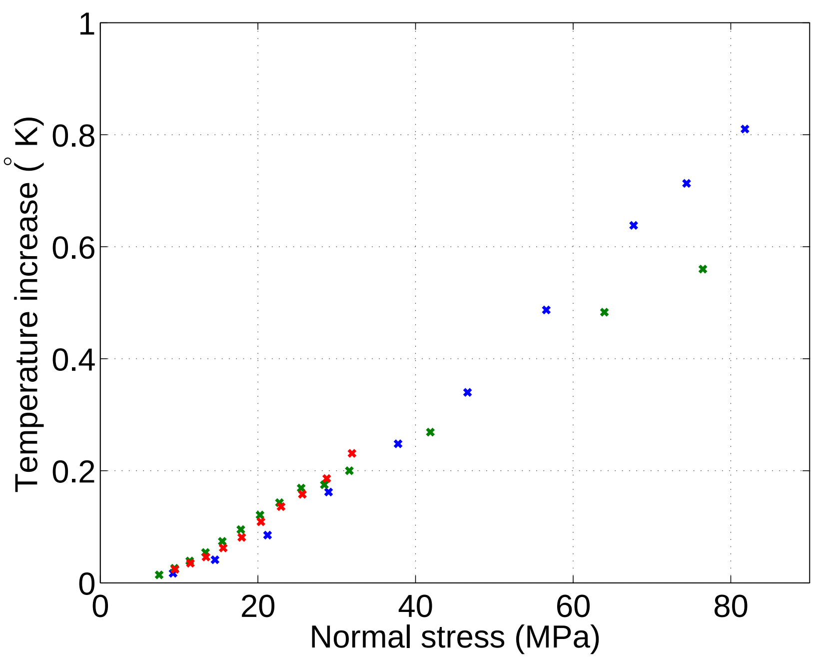


FIGURE 7. Measured relationship between applied dynamic stress and crack heating

converted to normal stress and plotted against observed crack heating. This is illustrated in Fig. 7 which shows crack heating as a function of dynamic normal stress for one of the tuned ETC specimens.

CONCLUSION

A valid POD model for vibrothermography will have to account for the crack motion as it is fundamental to the observed heating. The use of resonance makes it possible to obtain quantitative stresses with a single point vibrometer measurement. Careful experimental design can allow observation of the direct relationship between vibrothermographic crack heating and actual crack motion. Once this relationship has been observed and quantified in test specimens it may be possible to meaningfully extrapolate POD data by applying the relationship to the measured vibrations in a vibrothermographic test of an actual turbine part.

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